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Covering the Period

May 1, 1966 - October 31, 1966

Submitted by: Alan H. Barrett

Principal Investigator

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Massachusetts Institute of Technology

Research Laboratory of Electronics

Cambridge, Massachusetts

This report covers the period from May 1, 1966, to October 31, 1966, during which research was performed under National Aeronautics and Space Administration Grant NsG-419. Progress in the principal areas of investigation is briefly reviewed below.

1. <u>K-band Observations of the Planets and Sun</u>

A. Observations of Venus and Jupiter

The 1-cm wavelength spectrum observations of Venus and Jupiter which were made during the period from January to March, 1966 have been reduced.[1,2,3] The five-channel microwave radiometer and 28-foot paraboloid antenna have been described earlier.[4]

Venus and Jupiter were observed on 13 and 7 days respectively. The average spectra are listed in Table 1 together with the estimated rms errors. These measurements were calibrated by comparison with the lunar spectrum, as interpreted with the aid of antenna pattern measurements. The measurements were corrected for atmospheric absorption with an accuracy of approximately 1 or 2 percent using a concurrent series of solar-extinction atmospheric absorption measurements and measurements of ground-level humidity. The average spectra of these planets exhibit no resonant features significantly larger than the rms uncertainty of the data. The spectrum of Venus furthermore did not exhibit any narrow spectral features which varied more than 30°K during the experiment.

The Jovian spectrum does show some tendancy to exhibit an absorption resonance near 22.23 GHz when one face of Jupiter is toward the Earth. The data are inconclusive however. Both water vapor and ammonia have strong

Table 1-1

Results of Planetary Spectrum Measurements

Frequency (GHz)	Venus $\overline{T}_B$ (°K)	rms Error Rel. (%)	Abs. (%)	Jupiter $\overline{T}_B$ (°K)	rms Error Rel. (%)	Abs. (%)
19.0	477	8	12	105	20	20
21.0	451	4	9	106	9	10
22.235	436	4	9	98	10	11
23.5	418	4	9	116	8	9
25.5	400	4	9	123	7	9

resonances near 22.23 GHz.

B. Observations of the Sun.

The solar spectrum was determined by comparison of the observed solar and lunar brightness temperatures, as corrected for the effects of the antenna pattern, lunar phase, and atmospheric absorption.[5,6,7] The average of 8 days of observations is listed in Table 1-2. The spectrum did not vary much over this four-week period. The rms absolute error is approximately $\pm$ 700°K. This data is consistent with observations made by others outside this frequency interval.

Table 1-2

Observed K-band Central Solar Brightness Temperature

Frequency (GHz)	Average Brightness Temperature (°K)	Relative rms Error (°K)
19.0	10,800	$\pm$ 400
21.0	10,800	400
22.2	11,000	500
23.5	10,700	500
25.5	9,800	300

References:

1. Staelin, D.H., R.W. Neal, S.E. Law, and E.C. Reifenstein, Quarterly Progress Report No. 83, Res. Lab. of Elec., M.I.T. (Oct. 15, 1966) pp 10-14.

2. Staelin, D.H., and E. C. Reifenstein, Nerem Record, IEEE Catalogue No. F-70 (November, 1966) pp 138-139.

3. Staelin, D.H., and R.W. Neal, Astron. J., 71, 9, 872 (1966) (Abstract).

4. Staelin, D.H., and A. H. Barrett, Astrophys. J., 144, 352, (1966) pp 352-363.

5. Sullivan, W.T. III, Nerem Record, IEEE Catalogue No. F-70 (November, 1966) pp 142-143.

6. Sullivan, W.T. III, S.B. Thesis, Department of Physics, M.I.T., June, 1966.

7. Staelin, D.H., N. Gaut, S. Law, and W.T. Sullivan III, Quarterly Progress Report No. 84, Res. Lab. of Elecs., M.I.T. (January 15, 1966).

2. K-band Observations of the Terrestrial Atmosphere

A. Search for Stratospheric Water Vapor

Observations of atmospheric absorption were made during the summer of 1965 at frequencies of 21.9, 22.2, 23.5, 29.5, and 32.4 GHz using the equipment and solar extinction technique described earlier. Comparison of the absorption at 21.9 and 22.235 GHz indicated that any stratospheric water vapor contributed less than approximately 0.01 db zenith attenuation on each of 24 observing days. Since the water vapor resonances predicted on the basis of early radiosonde measurements of stratospheric water vapor were not found, it suggests that these early radiosonde measurements may have been in error . The more sensitive multichannel spectrometer now being assembled will eventually be used for a more careful search for the effects of high-altitude water vapor.

B. Integrated Water Vapor Content of the Atmosphere

One parameter of meteorological interest is the integrated water vapor content in a vertical column of the atmosphere. Single-frequency measurements of atmospheric opacity can not yield this parameter however, as is evident from the water vapor weighting functions described earlier.[1] A mathematical test was conducted to determine how accurately the integrated water vapor content could be determined using observations made at two or three frequencies simultaneously. The test involved comparison of the actual water vapor contents of 24 model atmospheres with the contents deduced from the theoretical spectrum values at the chosen frequencies. The model atmospheres were those measured by radiosondes during the summer of 1965.

In Table 2-1 are shown the equations used for computing the integrated water vapor content ρ (gm/cm^2) in terms of the measured opacities $\tau_{\nu(GHz)}(db)$. The rms percentage error is also shown for the two- and three- frequency cases.

Table 2-1

Expressions for Integrated Water Vapor Content of the Atmosphere

		rms error %
CASE I	$\rho\left(\frac{gm}{cm^2}\right) \triangleq 1.110\ \tau_{21.9} + 8.850\ \tau_{29.45}$	2.9
CASE II	$\rho\ \frac{gm}{cm^2} \triangleq 0.385\ \tau_{22.235} + 2.161\ \tau_{23.5} + 4.322\ \tau_{29.45}$	1.2

The rms error includes the effect of uncertainties in the atmosphere temperature and pressure profiles, and the effect of using only a finite number of frequencies. In practice the rms error would be increased somewhat by measurement errors, which are typically 0.01 db rms.

C. Atmospheric Emission Measurements

In the summer of 1966 the fine-channel K-band radiometer was rebuilt and mounted beside an open window on the M.I.T. campus. A small horn antenna was pointed out through the window such that the system was sheltered during rainstorms, and such that nearly all antenna sidelobes were directed or reflected toward the sky. The atmospheric emission spectrum was observed at approximately 30° elevation during all kinds of summer weather including thunderstorms. Typical preliminary spectra are listed in Table 2-2.

Table 2-2

Average Sky Brightness Temperature near 30° Elevation

Date (GHz)	Frequency (GHz) 19.0	21.9	22.265	23.5	32.4	Absolute Humidity (gm/m^3)	Weather
8/2/66	35	107	111	94	52	17.6	Overcast
8/2/66	46	124	126	113	65	15.0	Very Light Rain
8/3/66	245	265	266	269	278	17.8	Heavy Rain
8/3/66	51	123	129	116	80.	16.4	Slackening Rain
8/3/66	16	55	55	48	37	13.8	Clear Skies

The spectra have not yet been compared to theoretical models, but they do exhibit a strong resonance feature centered at 22.23 GHz and a non-resonant component, approximately proportional to ν^2, which increases strongly as the rainfall rate increases.

References:

1. Staelin, D.H., J. Geophys. Res., 71, 12 (1966) pp 2875-2881.

2. Barrett, A.H., and V.K. Chung, J. Geophys. Res., 67, 11 (1962) pp 4259-4266.

3. Oxygen-Line Observations at High Altitudes

The analysis of the data taken during balloon flights 150-P, 152-P, 153-P, and 154-P in July 1965 has been completed. No useful data for the ascent portion of 150-P were taken due to an equipment problem. Float and descent data are difficult to reduce fro this flight since final calibration temperatures are determined during the ascent portion of the flight. The other line-shape experiment, flight 154-P, was successful in every respect. Preliminary results of this flight were described in the previous Semiannual Report.

An inversion technique allowing the atmospheric absorption coefficient to be inferred from the results of flight 154-P has been developed This method yields results accurate to about ± 15% for absorption in the wings of the resonance line. The results of the inversion of the 154-P data indicate an absorption that is about 1.5 times the value predicted by the Van Vleck-Weisskopf theory for frequencies three or more line widths from the resonance frequency. This affirms our earlier contention of larger absorption in the line wings. The discrepancy probably lies in the assumption of the validity of summing the absorption of individual lines because of their mutual incoherence. It appears possible to obtain an empirical fit to the data by using the Van Vleck-Weisskopf line shape

$$f(\nu) = \frac{1/\Delta\nu}{\left(\frac{\nu-\nu_o}{\Delta\nu}\right)^2 + 1}$$

with the line width parameters, $\Delta\nu$, equal to the measured value for $\left(\frac{\nu-\nu_o}{\Delta\nu}\right) < 2$, equal to 1-5 times the measured value for $\frac{(\nu-\nu_o)}{\Delta\nu} > 3$, and a transition region between. More work continues in this area.

Flights 152-P and 153-P were experiments to obtain antenna temperatures at a float altitude of 40 km capable of being inverted to give the atmospheric temperature profile between 16 and 38 km. Observations were made at two nadir angles (0^o and 60^o) and at three frequencies ($\pm$ 20, $\pm$ 60, $\pm$ 200 MHz) centered on the 9^+ resonance at 61.151 GHz. A consistent discrepancy between the antenna temperatures for the 0^o observations and those of the 60^o observations exists and is probably due to use of a somewhat inaccurate antenna pattern in computing the theoretical curves. For this reason each of these flights has been treated as being two-three channel experiments rather than one-six channel experiment. A program to measure the antenna patterns mounted on the radiometer is underway.

Analysis of flights 198-LP, 199-LP, and 200-LP undertaken from Phoenix, Ariz., during Feb., 1966, continues.

The two balloon flights planned for the Summer of 1966 were successful. Flight 243-P was launched from the NCAR Balloon Base, Palestine, Texas at 0609 CST on August 17, 1966. After a flight duration of 9 1/2 hours the gondola was recovered in good shape 10 miles SE of Sonora, Texas. Flight 244-P was launched at 0529 CST on August 26, 1966. After a flight duration of 8 1/2 hours the gondola was recovered in good condition 15 miles NE of San Angelo, Texas.

These flights were different in several respects from other temperature profile experiments. Observations were made at two nadir angles (0^o and 75^o) and at three frequencies ($\pm$ 20, $\pm$ 60, $\pm$ 275 MHz) centered on the 21^+ resonance at 64.678 GHz. This line, being much weaker than the 9^+ line which was used

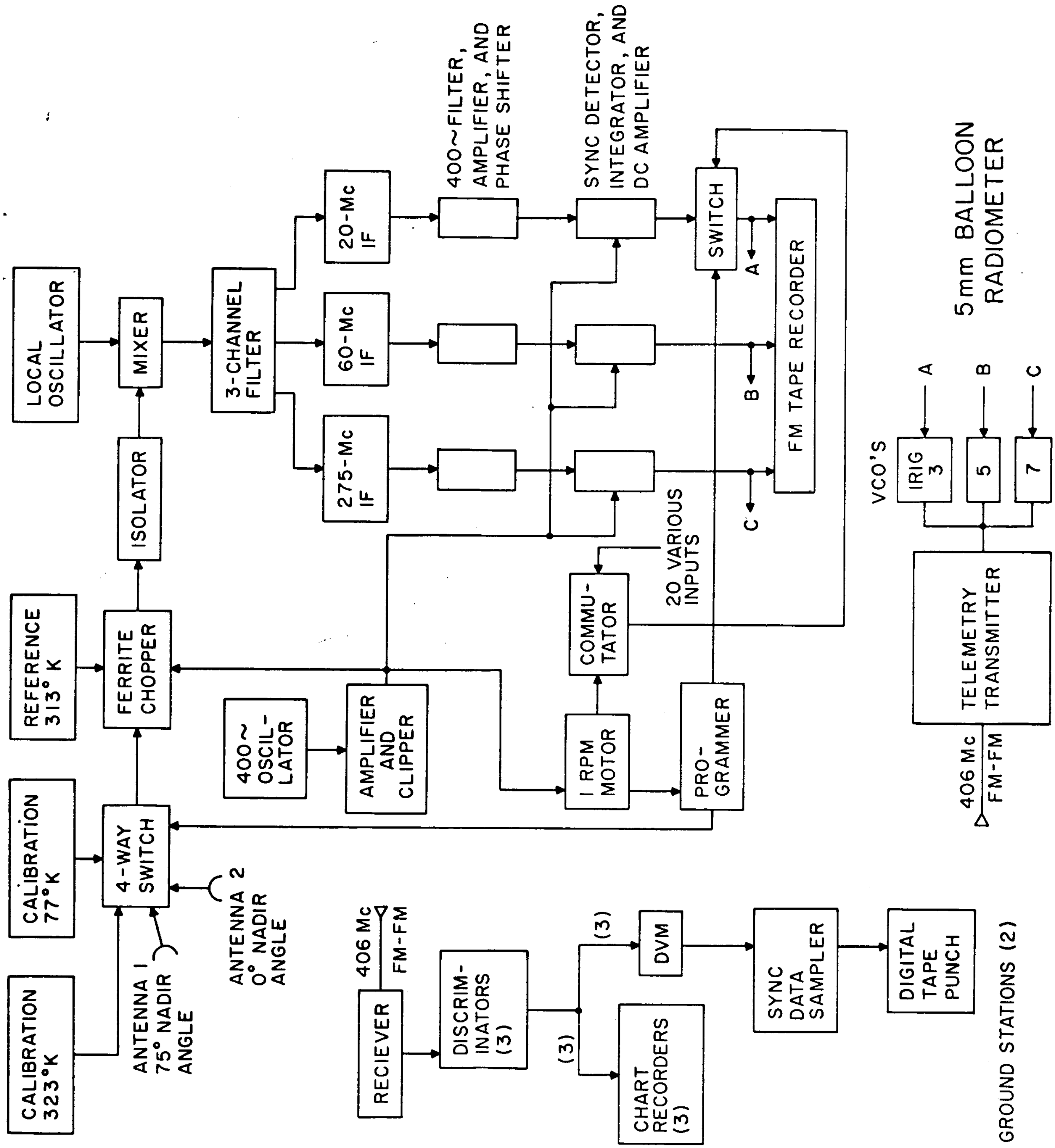

Figure 1

Block diagram of oxygen line radiometer.

in previous flights, permits soundings to penetrate below the tropopause. A summary of the parameters of the experiment was presented in the previous report.

Several changes were made to the radiometer for these flights. The local oscillator frequency was changed to 64.678 GHz, necessitating recalibration of all microwave components at the new frequency. A new ferrite chopper was installed and a different hybrid section for the mixer was built. The audio amplifier, synchronous detector, integrator, and dc amplifier stages were triplicated so that the three IF frequencies would be in operation simultaneously rather than singly. This resulted in three times the amount of data for a flight with the same duration as previous ones. A block diagram of the flight radiometer is shown in Figure 1.

Analysis of the data from these flights is underway.

The early results of this program have been published (A.H. Barrett, J.W. Kuiper, and W.B. Lenoir, J. Geophys. Res. 71 (20), 4723-4734, Oct. 15, 1966). The later results will be presented at the Annual Meeting of the American Geophysical Union in Washington, D.C., in April, 1967.

4. Temperature Profile by Inversion of Microwave Measurement.

A method of inferring the atmospheric temperature profile from balloon or satellite-based microwave measurements near 60 GHz has been developed. If microwave brightness temperature measurements were made at n frequencies by a balloon or satellite-borne radiometer directed toward the nadir, these brightness temperatures would be given by

$$T_{B\,i} = \int T(h)\, WF\, (h,\, \nu_i)\, dh \; ; \; i = 1, \ldots n \qquad (1)$$

where the weightin function, WF, depends on the temperature and pressure profiles. The temperature profile is approximated by

$$T(h) = f_0(h) + \sum_{j=1}^{n} a_j f_j(h), \tag{2}$$

where the f's are known functions of height and the a's are coefficients to be determined. Equation (2) is inserted into Equation (1) with the measured T_B's and the WF's computed from a model atmosphere. The resulting matrix equation is solved for the a's. New WF's are computed with T(h) from Equation (2) and the procedure repeated to find new values of the a's. This iterative process is continued until either a convergent or divergent sequence is evident. When the process converges, Equation (2) represents the inferred temperature profile which can be compared to the true one, if known.

The three main considerations of the process are:

1. How well can Equation (2) represent true temperature profiles?
2. In the absence of noise, how close to this best fit will the inversion come?
3. What effect will radiometric noise have?

These three questions have been answered, in part, on the basis of computer simulated experiments. Furthermore, inversion of the results of flight 152-P resulted in a good fit of the inverted profile to the true profile. It appears that inverted profiles with rms errors of 1-2 times the radiometric sensitivity (ΔT_{rms}) are possible. Work continues on these problems.

5. Observations at Four Millimeters Wavelength.

A program of cooperative research has been started with the Microwave Physics Laboratory of the Air Force Cambridge Research Laboratories (AFCRL), Bedford, Massachusetts, whereby radio astronomical observations at 4 mm wavelength are to be conducted. The 4 mm radiometer has been developed and built under this NASA grant and the observations will utilize the 29-foot radio telescope at the Prospect Park Field Station, Waltham, of AFCRL. Preliminary pattern and gain measurements using the radiometer and radio telescope indicate an antenna gain of approximately 72 db, a value entirely adequate to justify additional effort to bring the entire system up to its full usefulness at this wavelength.

AFCRL plans to use the 4 mm radiometer, in conjunction with its own 8 mm radiometer, to observe the sun. MIT personnel, in cooperation with AFCRL personnel, plan to observe the planets and the strong radio sources.

6. OH Interferometry.

In order to investigate further the physical conditions responsible for the anomalously intense sources of 18-cm line emission at radio frequencies, an interferometric study was undertaken jointly with M.L. Meeks and G.M. Hyde of Lincoln Laboratory, M.I.T., to determine the angular dimensions of the emitting regions. The interferometer was composed of the Millstone (84-ft) and Haystack (120-ft) antennas of Lincoln Laboratory, with a baseline of approximately 3800 λ at 18 cm, along a line nearly 20° east of north. Most of the observations were made with both antennas circularly polarized in the same sense.

The signals from the two antennas were effectively crosscorrelated by a phase-switching scheme. The sum and difference of the IF outputs from the two receivers were autocorrelated, and the difference between these autocorrelation functions was taken. A common local-oscillator signal was derived from reference signals carried along a transmission line that was servo-controlled to maintain constant electrical length. An IF delay for white-fringe compensation was unnecessary, since the delays were reconstructed in the autocorrelator. Fringe amplitude and phase information, as a function of frequency, was extracted from the autocorrelation functions by means of a least-squares-fit technique executed by a digital computer. After calibration of the baseline parameters with continuum radio sources of small diameters and known positions, the positions of the emission lines were obtained from fringe phase as a function of hour angle.

The observations have been concentrated, thus far, on the emission regions near the continuum radio sources W3 (IC 1795), W49, Sgr A, and NGC 6334. Table II-1 shows, for the five strongest lines at 1665 MHz in W3, the size limits (under the assumption of a uniformly bright circular disc) of the emitting source derived from the observed fringe amplitude. The uncertainty in fringe amplitude represents the peak observed deviation for 15-minute integration intervals over all local hour angles. All lines had nearly the same phase which allows us to put an upper limit on the angular separation of the individual lines. No significant resolution of the emitting source could be detected, and all of the radiation appears to orfginate from the same region. More limited observations of the 1667-MHz lines gave the same position for the lines at -42.2 Km/sec and -44.7 Km/sec within 10 seconds

Table II-1. Angular sizes and separations of emission features observed adjacent to W3.

Line Velocity[a] Km/s	Polarization (I.R.E. Convention)	Fringe Amplitude	Effective Source Diameter	Separation from -45.1 Km/s Line
-45.1	Right	1.01 ± 0.05	<15"	
-43.7	Right	1.0 ± 0.1	<20"	<3"
-41.7	Right	1.0 ± 0.2	<25"	<3"
-45.4	Left	1.0 ± 0.1	<20"	<3"
-46.4	Left	1.0 ± 0.1	<20"	<3"

[a]Velocity relative to the local standard of rest under the assumption that rest frequencies are those of the $^2\Pi_{3/2}$, $J = 3/2$, -doublet of $O^{16}H^1$.

of arc, subject to a possible lobe ambiguity owing to the small local-hour-angle coverage of the observations at this frequency.

Since all hour angles were covered at 1665 MHz, the position was unambiguously determined from the observations made June 7th through June 19th (Epoch 1950.0) to be

$$a = 02^h\ 23^m\ 14.3^s \pm 1.5^s$$

$$\delta = 61^\circ\ 38'\ 57'' \pm 10''.$$

The dominant contribution to these errors arises from uncertainty in the derived interferometer baseline. The rms fluctuations (for a 15-minute integration) because of noise in the observations of the strongest line (-45.1 Km/sec) was 3 per cent in fringe amplitude and 3° in fringe phase.

A search was made in the Palomar Observatory Sky Atlas, for possible optical identifications. The observed position falls just within the boundary of the nebulosity, midway between two faint stars, neither of which is within the position uncertainty.

The source of the line emission is clearly of an unusual nature. For example, the observed angular size limit implies a brightness temperature of at least 2×10^{6} °K for the line at -45.1 Km/sec. The apparent linear dimension of the source, under the assumption that it is located at the distance of W3 (1700 parsec), is less than 0.1 parsec. Sgr A is also a single point source, less than 20" in size. W49 and NGC 6334 each appear to be slightly more complex, and are apparently each double. The individual components are, however, unresolved by the interferometer.

In summary, all OH emission sources observed thus far are of very small angular size, although more than one point source can be associated with a given H II region. Each point source usually has more than one velocity component associated with it.

7. Low-frequency Aperture Synthesis of Discrete Radio Sources.

A program of observations has been completed at the National Radio Astronomy Observatory, Green Bank, West Virginia. The fringe visibilities of approximately 24 of the brightest radio sources, at a frequency of 234 MHz, were measured using the long-baseline interferometer with additional equipment constructed at M.I.T.

The NRAO interferometer consists of two radio telescopes, of 85-ft diameter, capable of operating at any of 6 baselines from 1200 m to 2700 m in separation, along an azimuth of $\sim 50^{\circ}$ ($H = 4^{h}\ 50^{m}$, $D = 22^{\circ}\ 07'$ approximately). The receiver was of the double-sideband variety, with an intermediate frequency band of 2-12 MHz. The telescopes were fitted with 234-MHz feeds and front-end electronics, which then led into the NRAO IF delay and correlation system. The first stage in the processing of the data was finished at NRAO, and the remaining work is being done here at M.I.T. From the results of these observations, the structures of many of these sources are being obtained by a variety of digital-computer processings, including smoothing, interpolation, inverse Fourier transformation, and model fitting.

For the most part, small extragalactic sources were selected for this program in an attempt to detect larger-scale diffuse halos around the major components that might be depositories for old, lower-energy electrons or the residues of events that preceded those responsible for the major components of the radio sources observed at present. The ultimate angular resolution (for those sources for which maps c an be obtained) will be of the order of 1 min (arc), compared with the 2-5 min (arc) sizes of the major components. In some cases the primary beam of the telescopes (diameter = 3° (arc)) included other comparable sources besides the one of interest, and the large minimum spacing of the interferometer (1200 m = 960 wavelengths) will not allow the several sources to be separated (a problem analogous to the multiple responses of a grating array).

Alan H. Barrett
Principal Investigator